

THE MINIMUM TEMPERATURE AT THE BASE OF THE STRATOSPHERE.

By W. J. HUMPHREYS.

One of the surprises that has come from sounding-balloon data is the evidence of a minimum temperature in the lower portion of the stratosphere. It has been thought that this recorded minimum is not real—not indeed in the air—but merely the effect of an instrumental error due to the gradual insolation warming of the thermograph under insufficient ventilation. Some records undoubtedly have been seriously affected in this manner, and it may well be conceded that none obtained in full sunshine is wholly free from temperature errors. Nevertheless, such errors are not sufficient to account in full, nor even in large part, for the decided temperature minima often recorded at and next above the base of the stratosphere.

If, however, it be affirmed that the vertical temperature distribution in this region is substantially as shown, which the accumulated records, including night records, require, then the obligation is thereby assumed of explaining how it is possible for a layer of air to be, so much of the time, colder than the atmosphere either above it or below. Such a layer certainly could neither be established nor maintained in a medium so nearly homogeneous in composition as the atmosphere by any known process of radiation or absorption. The explanation, therefore, of this minimum temperature, must be sought in some dynamical process. Nor, indeed, is it far to seek, for its nature appears to be indicated by the fact that the minimum temperature in question is essentially a phenomenon of the anticyclone, as is clearly shown in figures 2 and 3 of the article in this REVIEW, pages 159 and 160, on "Temperatures, pressures, and densities of the atmosphere at different levels in the region of northeastern France."

Now, whatever the origin of the anticyclone, one of its essential features is an extensive movement of air from higher latitudes toward lower. This air, therefore, because of the rotation of the earth, loses more or less of such eastward component of its velocity as it may have had. Hence it lags in its west-to-east flow and thereby acts as a partial barrier to the westerlies. These latter, in rising over this barrier, attain unwonted heights and consequently the topmost layers cool dynamically to temperatures below that which would put them in thermal equilibrium with the outgoing radiation; that is, below the normal temperature of the stratosphere. As such air runs forward it must produce at least three effects: (a) It must load that portion of the atmosphere over which it flows, and thus produce high pressure, with descending and dynamically warmed air below; (b) it must, in some measure, lift and, thus, through the consequent pressure readjustment, dynamically cool the stratosphere; and (c) it must establish, and in part itself constitute, a layer of minimum temperature at the bottom of the stratosphere. An exactly similar effect may also be produced, in some cases, by air on the forward side of a cyclone, as a result of its increased eastward velocity induced by its travel to higher latitudes.

This abnormally cold layer obviously is soon warmed to some extent by radiation, but as the intervals between anticyclones generally are only a few days, it follows that the lower portion of the stratosphere usually is colder than is the atmosphere either next above or below—colder because of endless repetitions at short intervals of dynamic expansions that always chill the topmost overflow beyond the limits of thermal equilibrium.

WHY THERE ARE NO CLOUDS IN THE STRATOSPHERE.

By W. J. HUMPHREYS.

The very frequent occurrence of cirrus clouds at and immediately below the base of the stratosphere makes it certain that during much of the time the atmosphere at this level is fully saturated. One might, therefore, suppose that the stratosphere, even if wholly devoid of vertical convection, would eventually also become saturated through long-continued diffusion. But the temperature of at least the lower portion of this region often drops 10° C., or more, with no evidence whatever of the formation in it of even a slight haze. Hence it would seem (a) that the stratosphere is so nearly devoid of condensation nuclei that it can become two to three fold supersaturated without appreciable condensation; or (b) that the difference between the amounts of water vapor that would produce saturation at the temperatures before and after cooling, -55° C. and -65° C., respectively, say, is not sufficient to produce a noticeable haze; or (c) that the assumption that the stratosphere is even approximately saturated is in error.

It will be convenient to consider these alternatives in the order given.

The idea that the absence of clouds in the stratosphere may be owing to the lack of condensation nuclei appears to be rendered untenable by the fact that in addition to the cosmic, or meteoric, dust always present, it occasionally contains also vast quantities of volcanic dust, and that even at such times it develops no clouds.

To test the second of the above alternatives—that is, whether or not the supposed condensation would produce a perceptible cloud—it is necessary to consider the effect of the possible amount of condensed water vapor on visibility. Let the initial temperature of the stratosphere be -55° C. and let it be temporarily cooled to -65° C., a supposition in approximate accord with actual occurrences. At -55° C. saturation pressure (expressed in terms of the height of a balancing column of mercury) is 0.0153 millimeter. At -65° C. it is 0.0038 millimeter, and the corresponding amounts of water vapor per cubic meter 0.02028 gram and 0.00528 gram, respectively. Hence on cooling from the higher to the lower of these temperatures there should appear (allowing for temperature contraction of volume) 0.01525 gram of ice crystals per cubic meter. Now it has been found¹ that, roughly, 0.3 gram of fog particles per cubic meter limits vision to about 90 meters. If, then, the ice crystals were the same size as the fog particles referred to the above computed quantity should limit vision to less than 2 kilometers. But it is also known that ice crystals formed at such low temperatures generally are much smaller than the average fog droplet, and therefore a decidedly more restricted vision should be anticipated. At any rate, it appears quite certain that if the strato-

¹ Wagner, Sitz. der K. Akad. der Wis. Wien, 117, p. 1290, 1908.

sphere were saturated at -55°C ., approximately its average temperature in middle latitudes, any considerable lowering of its temperature, such as often occurs, would produce in it a decided haze, or cloud, such as, in fact, never appears in that region.

Clearly, therefore, clouds do not form in the stratosphere for the simple and sufficient reason that its relative humidity is very low. But this answer raises the further query: Why is this region so very dry and how is it kept so?

As there obviously is little or no vertical convection in the stratosphere it follows that each of its gaseous constituents must be distributed substantially as it would be if it alone were present. Assume, then, that this region begins at 11 kilometers above sea level, and that its temperature is -55°C . Furthermore, let there be saturation at and immediately below its base. Under these assumed conditions what would be the state of humidity of the stratosphere?

As stated above, saturation pressure at -55°C . is 0.0153 millimeter. Hence, assuming the temperature of the stratosphere to be the same throughout, it follows, from the hypsometric equation, that, under the action of gravity, the pressure of the vapor, to which, at constant temperature, its density is directly proportional, must decrease with elevation substantially as indicated by the broken-line curve of figure 1. That is, even under the above-assumed favorable conditions, the action of gravity would, of itself, prevent the stratosphere from becoming saturated—the maximum possible amounts of vapor at different elevations being those indicated by the curve just referred to.

But suppose this maximum humidity of the stratosphere should be attained, what would be the effect of cooling it 10°C ., say, a drop in temperature that often occurs through at least its lowest several kilometers? To answer this question saturation pressures at different temperatures have also been given in figure 1. These are marked by dots, which, over the range taken, and for the indicated equal spacing of a constant temperature difference, fall, as shown, nearly along the curve of gravity distribution of vapor pressure. A mere inspection of this diagram shows, on the basis of the calculation made above, that under the assumed conditions the stratosphere would develop a dense haze. Hence, the actual humidity of this region must be far less than even the very limited amount possible under the restriction of gravity.

As is well known, during the passage of an anticyclone the lower portion of the stratosphere generally is considerably cooled. At each such time, therefore, all vapor that might be present in excess of that necessary to produce saturation at the current reduced temperature would be condensed out in the form of ice spicules that would slowly sift down. A sufficient subsequent increase of temperature, such as is also of frequent occurrence, would

lead to the re-evaporation of these ice crystals and permit further diffusion of water vapor into the stratosphere from lower levels. But the next (never long delayed) drop in temperature would again precipitate the excess moisture, and so on indefinitely. And as the falling of ice crystals, though slow, is more rapid than the diffusion of water vapor, it follows that the stratosphere, even if initially fully saturated, would soon become excessively dry, soon attain and then indefinitely maintain a vapor

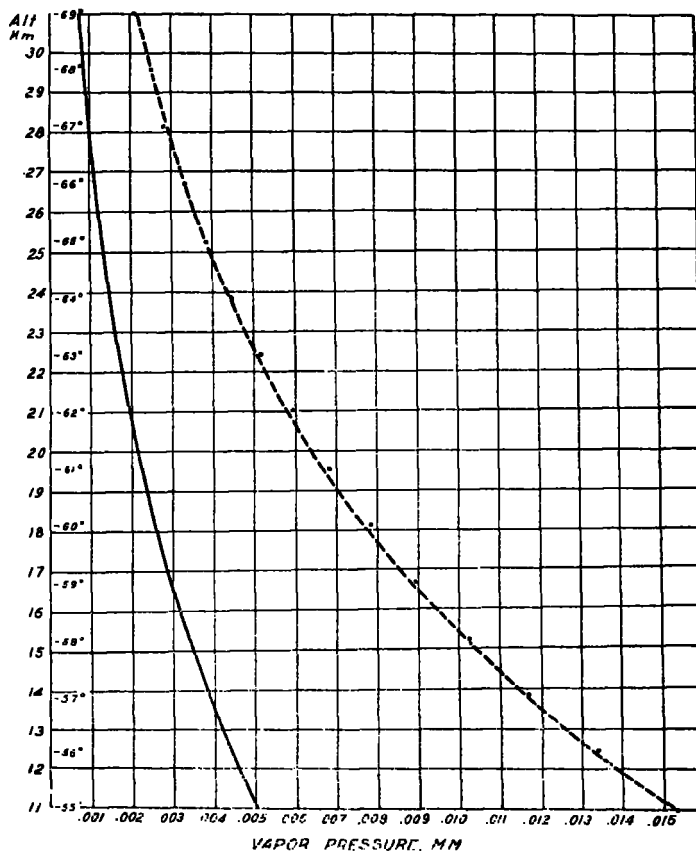


FIG. 1.—Gravity distribution of water vapor at constant temperature.

distribution more or less closely that indicated by the full line curve of figure 1, corresponding to a temperature of the stratosphere of -63°C .

It appears, therefore, that the clear, deep blue skies, typical of anticyclones, are owing to the extremely low humidity of the stratosphere; a condition maintained by the "cold waves" of this region that occur so frequently that there can never be any appreciable accumulation in it of vapor beyond that of saturation at even below the average of these minimum temperatures.